APPENDIX B

MODELS

Section I. Numerical Models

B-1. Introduction. Numerical models use computational methods to solve mathematical expressions describing physical, chemical, and biological phenomena. Computational methods such as approximation and iteration performed by high-speed digital computers allow solution of complex equations that cannot be solved by analytical methods.

a. Numerical modeling provides much more detailed results than analytical methods and may be substantially more accurate, but it does so at the expense of time and money. However, once a numerical model has been formulated and verified, it can quickly provide results for different conditions. In addition, numerical models are capable of simulating some processing that cannot be handled in any other way. They are also limited by the modeler's ability to derive and accurately solve mathematical expressions that truly represent the processes being modeled.

b. The four types of numerical models that are pertinent in the investigation of the environmental impact of coastal shore protection projects include:

(1) Hydrodynamic models describe the velocity components, water surface elevations, and salinity (or any other conservative passive constituent) distributions within the study area.

(2) Sediment transport models predict the shoreline response (erosion or accretion) to man-made engineering structural or dredged channel modifications, and estimate the ultimate fate (resuspension, transport, and deposition) of dredged material disposed in an aquatic dredged material disposal site.

(3) Water quality models predict physical characteristics and chemical constituent concentrations of the water at various locations within the study area.

(4) Ecological models predict the interactions between water quality and the aquatic community.

c. The information derived from hydrodynamic models forms part of the data base for sediment transport, water quality, and ecological models, and the data from sediment transport and water quality models, in turn, form part of the data base for ecological models. Hence, it is essential that these foundation modeling activities be accomplished with adequate accuracy. The various described models require input data which may be classified as:

(1) Initial conditions. The data describe the initial state of the system prior to numerical modeling.

(2) Boundary conditions. The data specify the system geometry and the quantity and constituent concentrations of freshwater inflows or other depositions.

(3) Verification requirements. Any other data considered necessary for the verification (or calibration) of the numerical models.

B-2. Field Data.

a. Because no numerical model study can be more accurate than the information on which it is based, the importance of adequate field data cannot be overemphasized. The first steps in any numerical model study must be the specification of objectives: an assessment of the geophysical, chemical, and biological factors involved; and collection of data essential to describe these factors. Assessment and data collection should include:

(1) Identification of freshwater inflow sources, including their average, range, and time history distribution of such inflow.

(2) Assessment of the tides and tidal currents that exist within the region of interest.

(3) Evaluation of wind effects and other geophysical phenomena that may be peculiar to the specific study and that may contribute to aeolian sediment transport within or beyond the study boundary limits.

(4) Complete understanding of wave climate throughout the region of interest, including seasonal and annual distribution with frequencies of occurrence by height, period, and direction of approach.

(5) Knowledge of the resulting wave-induced currents.

(6) Evaluation of the effects of simultaneous occurrence of unidirectional flow (tidal currents or freshwater river inflow) and oscillatory currents (wave-induced particle motion).

(7) Assessment of effects and probability of occurrence of aperiodic extreme meteorological events such as severe storms or hurricanes.

(8) Identification of the sources of sedimentation and of the sediment types for development of a sediment budget analysis of the system under evaluation.

(9) Determination of sources and expected quantities and composition of industrial and municipal effluents, nonpoint contaminants, and tributary constituent concentrations.

(10) Identification and census of the aquatic community of the region, and the chemical, physical, and biological factors which influence its behavior.

(11) Archive of all available hydrographic, bathymetric, topographic, and other geometric data pertinent to preparation of numerical models.

b. The purpose of the preliminary assessment of pertinent and available data is to provide a basis for the selection of the models needed and for planning field data acquisition programs. The most satisfactory procedure is to plan the numerical modeling and field data acquisition program together. If possible, the basic hydrodynamic model should be operational during the period in which field data are being acquired. One major reason for concurrent model simulation and data acquisition is that anomalies in field data frequently occur, and the numerical model may be useful in identifying and resolving any such anomalies.

B-3. Data Analysis.

a. In conjunction with the field data acquisition program and the projected numerical modeling activity, a program of data analysis must be undertaken. For the data analysis program to be as efficient as possible, the field data should be recorded on media that can be automatically read by the computer equipment to be used for such data processing.

b. Data analysis includes isolation of the astronomical tide from the tidal record and for an identification of the decomposition of the constituents of the astronomical tide. The purpose of separating the astronomical tide from the observed tide is two-fold:

(1) This separation allows one to examine the residual and, by using statistical methods, to investigate the extent to which other geophysical phenomena, such as wind, influence the observed flow.

(2) The astronomical tide is deterministic and may be used in synthesizing tidal records for hypothetical events or during periods for which tide records are not available.

c. Three fundamental observations regarding data analysis should be considered:

(1) The astronomical tide is somewhat dependent on freshwater inflows into the study region, and the amplitude of the tidal constituents therefore tends to vary seasonally in many coastal areas.

(2) Past experience in the analysis of tidal data in conjunction with model studies has shown that a minimum of about 30 days of record for tidal elevation, velocity, and salinity data is essential for satisfactory analysis.

(3) Data should be synoptic, with all data stations being monitored during the same time period in order to properly verify the numerical models.

B-4. Hydrodynamic Models. Numerical models of hydrodynamic processes, sediment transport, and water quality processes are said to be coupled if they are applied simultaneously and interactively on a digital computer. The codes use the same spatial and temporal grid. If, conversely, the hydrodynamic model is run and the output from it used as input to the sediment transport or water quality model, the two models are said to be uncoupled. With uncoupled codes, the hydrodynamic output may be spatially and/or temporarily averaged and subsequently used as input to the water quality model. In many instances, it is more economical to run uncoupled models. Uncoupled models are unacceptable where thermal gradients or the concentration of dissolved or suspended material causes a large enough variation in the fluid density to substantially affect the flow.

a. General. The various numerical models may be classified as one-, two-, or three-dimensional. The one-dimensional models treat the system by averaging over a succession of cross sections. One-dimensional models are well suited to geometric situations such as channels with relatively uniform cross-sectional shape and with center lines whose radius of curvature is relatively large compared to the width, provided the water density is uniform over the cross section. Two-dimensional depth-averaged models are the type most commonly employed and are well suited to studies in areas such as shallow estuaries where the water column is relatively well mixed. Laterally averaged models are used in studies of relatively deep and narrow bodies of water with significant variation of density vertically through the water column. Three-dimensional hydrodynamic models are relatively new and have been applied to only a limited number of practical studies. In general, two-dimensional models are substantially more expensive to operate than one-dimensional models, and three-dimensional models are more complex and more expensive than two-dimensional models. Hence, in situations where it is known a priori that one of the simpler models will produce satisfactory results, the simpler model should be employed for economy.

b. Two-Dimensional Depth-Averaged Models. Two-dimensional depth-averaged models are most commonly employed in the investigation of tidal flows in inlets, bays, and estuaries. The two distinctly different formulations that have been employed are finite difference and finite element. Models currently being used at the Waterways Experiment Station (WES) include the finite difference model WIFM (WES Implicit Flooding Model), which evolved from early work by Leendertse (1967, 1973). The model and its application have been refined and significantly improved at WES, and have been described at different stages of development by Butler (1980). The finite element flow model of Research Management Associates (RMA-2V) (Ariathurai and Arulanadan 1978) evolved rom work by Norton et al. (1973) sponsored by US Army Engineer District, Walla Walla. The WES version of this model and a companion sediment transport model, STUDH, and their application to project studies have been described by McAnally et al. (1983). A user's manual for these finite element models and support programs (TABS-2) has been prepared by Thomas and McAnally

(1985). Most existing finite difference models employ cartesian coordinates which, even with variable grid spacing capabilities, may lead to undesirable approximations in schematization of complex study areas. Recent work by Johnson (1980) has resulted in a finite difference model VAHM (Vertically Averaged Hydrodynamic Model) for flow and transport which employs a generalized coordinate transformation technique called boundary-fitted coordinates to overcome this limitation. Development of this approach is continuing.

c. Two-Dimensional Laterally Averaged Models. Laterally averaged models are applicable in studies of relatively deep, narrow channels with small radius of curvature in which lateral secondary, currents of appreciable magnitude do not develop. Since fewer systems meet this criterion, work on models of this type has been more limited than on the depth-averaged models. However, work performed during the last few years has produced a useful model CE-QUAL-W2 (Environmental Laboratory, Hydraulics Laboratory 1986). CE-QUAL-W2 was originally developed as a two-dimensional laterally averaged free surface and heat conducting model (LARM) for computing reservoir flow patterns (Edinger and Buchak 1979). In more recent developments, the water density was allowed to be a function of both temperature and salinity, and estuarine boundary conditions were incorporated. This version was called LAEM (Edinger and Buchak 1981). LARM and LAEM were combined with multiple branching capabilities and renamed GLVHT (Buchak and Edinger 1983). WES included water quality algorithms and named the resulting code CE-QUAL-W2. These codes have been used to investigate the effect of navigational channel deepening on salinity intrusion in the Lower Mississippi River and the Savannah River estuary.

d. Three-Dimensional Models. Depth- and laterally averaged two-dimensional models obviously lack the ability to predict secondary flows involving the plane that has been averaged. In some instances, these secondary currents may be appreciable and affect such things as salinity intrusion, sediment transport, thermal distribution, and water quality. Leendertse et al. (1973) pioneered the development of one of the early three-dimensional models of an estuary. Leendertse ' s model employed cartesian coordinates. A three-dimensional model that utilizes stretched coordinates in both the horizontal and vertical directions has been developed and applied in studies of the Mississippi Sound (Sheng and Butler 1982, Sheng 1983). This model CELC3D (Coastal, Estuarine, and Lake Currents; Three-Dimensional) may be used to provide detailed computations of the currents within several tidal cycles or time scales of a storm event. For a scenario of repeatable hydrodynamics, CELC3D may be combined with the sediment transport algorithm for long-term computations on the order of weeks, months, or longer. Three-dimensional versions of the finite element flow and sediment models have also been developed and have been applied to several field sites (Ariathurai 1982, King 1982). Improvements in the efficiency of computational equipment and modeling technology are increasing the feasibility of applying three-dimensional models.

B-5. Sediment Transport Models. The transport of noncohesive and cohesive sediments under the simultaneous action of waves and currents takes place along natural beaches, coastlines, bays, estuaries, and elsewhere when waves become superposed upon currents. The currents may be wave-induced, wind-driven, tidal, and stream, or may originate from some other less cause.

a. CIP (Coastal and Inlet Processes Numerical Modeling System). Coastal processes of tides, waves, wave-induced currents, and sediment transport can be modeled by using the numerical modeling system CIP (Coastal and Inlet Processes). The system utilizes the WES Implicit Flooding Model (WIFM) for tides, the Regional Coastal Processes Wave Propagation Model (RCPWAVE) for waves, the model CURRENT for wave-induced currents, and a sediment transport model for transport of sediment due to the combined action of tides, waves, and wave-induced currents. All four models generally use the same computational grid for a given set of conditions.

(1) WIFM is a general, long-wave model which can be used for simulation of tides, storm surges, tsunamis, etc. It allows flooding and drying of land cells near the shoreline. It is a depth-averaged model so that variations in the vertical direction are averaged in the model. It is used to determine tidal elevations and velocities in the two horizontal coordinate directions.

(2) RCPWAVE is a linear, short-wave model which considers the transformation of surface gravity waves in shallow water, including the processes of shoaling, refraction, and diffraction due to bathymetry, and allows for wave breaking and decay within the surf zone (the region shoreward of the breaker line). Unlike traditional wave-ray tracing methods, the model uses a rectilinear grid so that model output in the form of wave height, direction, and wave number is available at the centers of the grid cells. This method is highly advantageous since the information can be used directly as input to the wave-induced current and sediment transport models, and the problem of caustics due to crossing of wave rays is avoided.

(3) CURRENT computes the wave-induced currents that result when wave breaks and decay in the surf zone. In general, such breaking induces currents in the longshore and cross-shore directions with resulting changes in the mean water level. These currents play a major role in the movement of sediment in the nearshore region.

(4) The sediment transport model predicts the transport, deposition, and erosion of sediments in open coast areas as well as in the vicinity of tidal inlets. It accounts for both tides and wave action by using for input the results of WIFM, RCPWAVE, and CURRENT in terms of tidal elevations and currents, wave climate information, wave-induced currents, and setups at the centers of grid cells. The model computes transport separately for straight open coast areas, and areas in the vicinity of tidal inlets. In the case of straight open coast areas, transport inside and outside the surf zone is treated separately.

(a) Transport inside the surf zone. Inside the surf zone, it is the wave-breaking process that is primarily responsible for the transport of sediment. This process is quite complex and not entirely understood. There is even disagreement on the primary mode (bed load or suspended load) of sediment transport in the surf zone. Thus, a model that determines transport in the surf zone must be empirical to some degree in its formulation. The surf zone transport model is based upon an energetics concept which considers that the wave orbital motion provides a stress that moves sediment back and forth in an amount proportional to the local rate of energy dissipation. Although there is no net transport as a result of this motion, the sediment is in dispersed and suspended state so that a steady current of arbitrary strength will transport the sediment. Thus, breaking waves provide the power to support sediment in a dispersed state (bed and suspended load), while a superposed current (littoral, rip, tidal, etc.) produces net sediment transport.

(b) Transport beyond the surf zone. Beyond the surf zone, waves are not breaking. Currents (tidal, littoral, rip, etc.) still transport sediments, but the sediment load is much smaller than the load in the surf zone. Waves still assist in providing power to support sand in a dispersed state. However, there is little turbulent energy dissipation, and frictional energy dissipated on the bottom represents most of the energy dissipation. Bed load is the primary mode of sediment transport beyond the surf zone. Since beyond the surf zone it is the tractive forces of currents (including wave orbital velocity currents) that produce sediment movement, an approach is applied which considers sediment transport by such currents which may exist in the area. Again, since the complete physics of the problem is not entirely understood, a semiempirical approach must be undertaken. To model this zone, the approach of Ackers and White (1973) is followed, after appropriate modification for the influence of waves.

(5) The CIP (Coastal and Inlet Processes Numerical Modeling System) has been applied by WES to the entrance region of Kings Bay Naval Submarine Base, Georgia. The sediment transport model was verified by comparing computed erosion and deposition rates in the navigation channel with those obtained from field surveys. There was good agreement both with respect to trends and magnitudes.

b. Shoreline Change Model. A numerical model for predicting shoreline evolution has been developed by Le Mehaute and Soldate (1980), which evaluates long-term three-dimensional beach changes. The combined effects of variations of sea level, wave refraction and diffraction, loss of sand by density currents during storms, by rip currents, and by wind, bluff erosion and berm accretion, effects of man-made structures such as long groins or navigation structures, and beach nourishment are all taken into account. A computer program has been developed with various subroutines which permit modifications as the state-of-the-art progresses. The program has been applied to a test case at Holland Harbor, Michigan.

c. N-Line Sediment Transport Model. An implicit finite-difference, N-Line numerical model has been developed by Perlin and Dean (1983) to predict bathymetric changes in the vicinity of coastal structures. The wave field transformation includes refraction, shoaling, and diffraction. The model is capable of simulating one or more shore-perpendicular structures, movement of offshore disposal mounds, and beach fill evolution. The structure length and location, sediment properties, equilibrium beach profile, etc., are user-specified along with the wave climate. The N-Line model has been used to simulate sediment transport of dredged material disposal in the vicinity of Oregon Inlet, North Carolina.

d. CELC3D Sediment Transport Model.

(1) The most recent advance in the area of mathematical modeling of coastal currents and sediment dispersion (resuspension, transport, and deposition), as well as the state of the art at the present time has been conducted by Sheng and Butler (1982) and Sheng (1983). An efficient, three-dimensional, and comprehensive numerical model of coastal currents, CELC3D (Coastal, Estuarine, and Lake Currents; Three-dimensional), has been developed and is operational. The authors have provided a thorough quantitative analysis of the role of turbulence in affecting the deposition, entrainment, and transport of cohesive sediments. Detailed dynamics within a turbulent boundary layer, under pure wave or wave-current interaction, has been studied by means of a turbulent transport model. Model predictions compare well with prototype data and are more accurate than simpler parametric models. Dispersions of sediment due to tidal currents, wind-driven currents, and waves have been studied. Waves were found to be generally more effective in causing entrainment (resuspension) of sediments.

(2) Physical models, field studies, and laboratory investigations were utilized to aid in the ultimate construction of CELC3D. Special features of CELC3D include:

(a) A "mode-splitting" procedure which allows efficient computation of the vertical flow structures (internal model).

(b) An efficient alternating direction implicit (ADI) scheme for the computation of the vertically-integrated variables (external mode).

(c) An implicit scheme for the vertical diffusion terms.

(d) A vertically and horizontally stretched coordinate system.

(e) A turbulence parameterization which requires relatively little tuning.

(3) Slowly varying currents and wave orbital velocities generally both contribute to the generation of bottom shear stress in shallow or intermediate waters. To remove empiricism from CELC3D simulation, Sheng (1983) used a dynamic turbulent model to predict the wave-current interaction within the bottom boundary layer. Calibration data were collected at a 90-meter water depth site about 1 kilometer off the California coast during the Coastal Ocean Dynamics Experiment (CODE-1) program. Due to the relatively long fetch from the north, high seas (6-8 feet) were typical, and wavelengths were sufficiently long for the wave to feel the bottom. Velocity profiles (averaged over 6-minute intervals) at this site showed typical logarithmic variation

with height above the bottom. The values of the frictional velocity, u_*, were typically between 0.22 and 0.66 centimeter per second. Using reference velocities at 1 meter, these u_* values correspond to drag coefficients of 0.019 and 0.026, respectively. Corresponding values of the effective roughness height, z_o , in the presence of waves are 1.3 and 3.0 centimeters, respectively. These values are an order of magnitude greater than the z_o based on physical roughness alone.

B-6. Water Quality Models. Historically, the analysis of water quality has concentrated on the dissolved oxygen (DO) and biochemical oxygen demand (ROD). The balance between DO and BOD concentrations was the result of two processes: the reaeration of the water column, and the consumption of DO in oxidation of BOD. Later emphasis has been on extending and refining the Streeter-Phelps formulation by using a more generalized mass balance approach and by the inclusion of additional processes such as benthic oxygen demand, benthic scour and deposition, photosynthesis and respiration of aquatic plants, and nitrification. The more comprehensive water quality models have been developed to include the nitrogen and phosphorus cycle and the lower trophic levels of phytoplankton and zooplankton. A number of investigations have modeled the algal nutrient silica. Selected chemical constituents have been modeled by assuming thermodynamic equilibrium. The fate of toxicants such as pesticides, metals, and PCB’s is very complicated, for they involve adsorption-desorption reactions, flocculation, precipitation, sedimentation, volatilization, hydrolysis, photolysis, microbial degradation, and biological uptake. Selection of a water quality methodology requires consideration of Water Quality Constituents and Dimensional and Temporal Resolution.

a. Water Quality Constituents. The water quality constituents most frequently simulated include salinity, light, temperature, DO, ROD, coliform bacteria, algae, nitrogen, and phosphorus. Each of these constituents interacts with the others, but the significance of their dependencies varies among constituents, and their inclusion in a numerical water quality model depends upon the study objectives and the water body under consideration. The environmental impact analysis of most coastal shore protection projects can use salinity and DO as indices of environmental change. Salinity plays a dominant role in physio-chemical phenomena such as flocculation of suspended particulates, is used as a variable to define the habitat suitability for aquatic organisms, and is frequently employed as a conservative tracer to calibrate mixing parameters. Dissolved oxygen is a respiratory requirement for most organisms and is used as a measure of the "health" of aquatic systems. Dissolved oxygen can be used to evaluate the environmental significance of stratification resulting from channel deepening and realignment of deep-draft navigation projects, or most other coastal shore protection projects.

b. Dimensional and Temporal Resolution.

(1) In a numerical water quality model the choice is between a one-dimensional model and one that incorporates two or three spatial dimensions.

A long, narrow, and vertically well-mixed water body may be represented by a one-dimensional model consisting of a series of segments averaged over the cross section. Where there is pronounced vertical stratification, it is likely that a laterally averaged two-dimensional model will be needed. In other situations where there are marked lateral inhomogeneities that are accompanied by pronounced stratification, a three-dimensional model may be required. Most existing water quality models are one-dimensional, Practical application of two-dimensional laterally and depth-integrated models has been made and is feasible. The Corps has recently developed and applied three-dimensional water quality models.

(2) The basis of all water quality models is a velocity field either specified by empirical measurements or computed by numerical hydrodynamic models. The current trend in hydrodynamic modeling is toward development of three-dimensional models with increased spatial and temporal resolution in order to resolve important scales and minimize the need for parameterization. As a result, modern time-dependent hydrodynamic models normally have time steps on the order of minutes to 1 hour. The chemical and biological equations of water quality models have characteristic time scales determined by the kinetic rate coefficients. These time scales are usually on the order of 1 to 10 days. The phenomena of interest, such as depletion of DO and excessive plant growth, occur on time scales of days to several months. Direct coupling of hydrodynamic and water quality models may provide unnecessary spatial and temporal resolution, and the high resolution water quality model results cannot be effectively interpreted or verified. Present field sampling programs resolve constituent concentrations on the order of a kilometer to tens of kilometers in the horizontal, meters in the vertical, and days to weeks in time. In addition, the kinetic rate coefficients presently used in water quality models resolve dynamics on the order of days to weeks.

c. Numerical Water Quality Models. Linkage of the hydrodynamics and water quality using the same spatial and temporal grid is practical with one-dimensional and some two-dimensional models even for long-term simulations. However, long-term water quality simulations are computationally very expensive when water quality is directly coupled to two-dimensional vertically averaged and three-dimensional hydrodynamic models. Therefore, the Environmental Laboratory has developed not only one-dimensional and two-dimensional laterally averaged numerical water quality models that use the same spatial and temporal grid used by the hydrodynamic driver but also a method for averaging fine scale hydrodynamic data to drive a coarser scale water quality model for two-dimensional depth-averaged and three-dimensional applications.

(1) CE-QUAL-RIVI is a dynamic, one-dimensional (longitudinal) hydrodynamic and water quality model originally developed for flows in streams. Recent enhancements included provision for tidal boundary conditions and reversing flows. The hydrodynamic and water quality codes are separate but use the same spatial and temporal grid. Simulated water quality constituents include temperature, DO, CBOD, organic nitrogen, ammonia nitrogen, nitrate nitrogen, orthophosphate phosphorus, coliform bacteria, dissolved iron, and dissolved manganese.

(2) CE-QUAL-W2 is a two-dimensional laterally averaged hydrodynamic and water quality model developed for reservoirs and estuaries (Environmental Laboratory, Hydraulics Laboratory 1986). The water quality coding is arranged into hierarchial levels of complexity, allowing the user to select the level of water quality detail desired for a particular study. The first level of complexity deals with conservative and noninteractive constituents (e.g., conservative tracer and coliform bacteria), the second level with DO-BOD or DO-nutrient-phytoplankton dynamics, the third with PH and carbonated species, and the fourth level with reduced chemical species.

(3) The MULTIPLE-BOX model method consists, of driving a finite segment, box-type water quality model with temporally and/or spatially averaged hydrodynamic output. The box model segment sizes, time step, and dispersion coefficients are adjusted to assure that transport with the box model adequately reproduces that of the finer scale hydrodynamic/transport model. The EPA's multiple-box model WASP (Water Quality Analysis Simulation Program) was selected as the transport framework for a versatile water quality model that could be interfaced with hydrodynamic model (Ambrose et al. 1986). WASP contains a variety of water quality kinetic algorithms that the user may select, including toxic substances. The WASP code may be applied in one-, two-, or three-dimensional configurations. The code does not compute hydrodynamics; the use of the WASP code requires hydrodynamic input. A methodology for spatially and temporally averaging hydrodynamic output is being developed by WES.

B-7. Ecological Models. Ecological models include numerous biological species and emphasis food chain and species interactions. No general ecological model exists. Existing ecological models are site-specific and dependent upon the local aquatic community. The Environmental Laboratory at WES serves as a clearinghouse for Corps inquiries and is becoming an active participant in ecological model application.

B-8. Modeling Systems.

a. Consideration has been given to some of the more important aspects of numerical model selection and application. Hydrodynamic, sediment transport, water quality, and ecological models may not be considered as individual entities. The various models must be coupled, or the output of one model must be used as input to a subsequent model. If the applicable models are to be used efficiently and economically, the data transfer between the models must be considered and steps must be taken to ensure output-to-input compatibility. In modeling there are, in addition to the modeling itself, data to be collected, analyzed, and put into appropriate data bases. Each of these activities requires substantial data processing, and the aggregate cost of these activities may far exceed the cost of the actual modeling exercise. Also associated with most studies are other requirements, such as reports, which lead to additional data processing for such activities as computer graphs. The development of the models and other programs requires a broad spectrum of technical talents, and the execution of a comprehensive study may require the interaction of several individuals.

b. A comprehensive, integrated system of modeling and utility programs, which are documented to the extent that the system may be understood and used by the various individuals participating in the study, is essential to an effective study. Such systems are emerging. The WES Hydraulics Laboratory has developed a system for Open Channel Flow and Sedimentation (TABS-2) that uses depth-averaged finite element models to predict hydrodynamics, salinity, and sediment transport. The WES Environmental Laboratory has developed the one-dimensional (CE-QUAL-RIVI), the two-dimensional laterally averaged (CE-QUAL-W2) (in conjunction with the Hydraulics Laboratory), and the arbitrarily dimensioned multiple-box model. The WES Coastal Engineering Research Center has developed and made operational an efficient, comprehensive, and three-dimensional numerical model system of coastal currents and sediment transport, CELC3D, which provides for the resuspension, transport, and deposition of coastal sediments where sediment particle dynamics is modeled by a consideration of particle groups and coagulation processes. The emergence of such comprehensive systems is a significant aspect of the advancement of numerical modeling of the environmental engineering aspects of coastal shore protection projects.

Section II. Physical Models

B-9. Physical Coastal Models.

a. Earlier sections of this EM discuss specific considerations that must be addressed to evaluate the impacts of coastal shore protection projects on hydrodynamics, sediment transport, water quality, biological, or ecological conditions. One of the tools that often is applied to make the necessary predictions of these conditions is the physical coastal model. This section provides a brief description of physical coastal modeling and its relation to other models. It is intended to familiarize engineers and scientists with the use of this technique in preparing impact studies. The relative strengths and weaknesses are discussed so that, depending on the specific situation, physical coastal models might be considered in a modeling strategy. The basis and methods used in physical coastal modeling are also briefly described.

b. For projects in which dependable, accurate results warrant the additional expense, a physical coastal model study is recommended. This approach is especially recommended if the system is partially mixed or stratified in vertical salinity structure, or if it has a complicated geometry. Guidance for initiating physical (hydraulic) models studies is given in ER 1110-2-8102, ER 1110-2-1403, and related ER’s. The Coastal Engineering Research Center’s comprehensive report by Hudson et al. (1979) discusses physical models to assist in the solution of complex coastal engineering problems. This report provides information for use by both the laboratory research engineer and the field design engineer on the capabilities and limitations of coastal hydraulic modeling procedures. The report is intended to provide sufficient information to document the state of the art of scale modeling practiced by WES. It is also intended for field design engineers and other laboratory research engineers to better understand the principles of scale models and the application of these principles in the design, construction, and operation of scale hydraulic coastal models in the solution of problems involving the interaction of waves, tides, currents, and related sediment movements in estuaries, coastal harbors, coastal erosion, and stability of coastal structures and inlets. Estuarine and coastal physical hydraulic model studies performed at WES usually require from 18 to 48 months, and cost approximately $20 per square foot of model to build, and approximately $20,000 per month to operate (1986 dollars).

c. Physical coastal models are scaled representations of a coastal problem area under study. Seawater supply, tide generators, wave generators, and gaged freshwater inflows are necessary appurtenances. The models are often molded in concrete between closely spaced templates, although many coastal models are constructed with movable-bed boundaries. Instrumentation may be mounted on the models or experimental samples may be withdrawn from the models to measure such attributes as water surface elevation, current speed and direction, salinity, and tracer concentrations. Water surface tracers and dye patterns are often photographed to qualitatively and quantitatively examine their behavior or patterns of flow.

d. Boundaries and features of models should be carefully planned. A physical coastal model is designed and constructed to include the region of interest and any other areas necessary so that boundary data or conditions can be satisfactorily applied. If the effects of assimilative capacity on the area of interest are to be tested, effluent outfalls or diffusers are included in model design and construction. If all the modifications to be tested in the model study are anticipated at the time of model design, provisions can be made to make them quickly and much less expensively.

B-10. Similarity Criterion.

a. In any coastal model study, the physical phenomena observed in the model should represent those phenomena occurring in the prototype, so that the prototype action can be predicted by operating the model. The general theory of model design is based on the fundamental principle that a functional relationship exists among all the variables associated with the system. Further, the number of variables can be significantly reduced by forming a complete set of dimensionless variables for which a new function expressing the relationship between the dimensionless terms exists. If the model is designed so that each of the dimensionless terms of the complete set is the same in the model as in the prototype, then the nature of the unknown function is identical for the model and the prototype. If all these conditions are satisfied, the model is considered a "true" model which provides accurate information concerning the behavior of the prototype.

b. Although space limitation for the construction of the model may sometimes dictate that the model be distorted, a physical model can usually be operated with the same linear scale in all three dimensions (i.e. an undistorted-scale model). This undistorted-scale model dictates that geometric similarity exists, as the ratios of all homologous dimensions on the model and prototype are equal. In addition to geometric similarity, a true undistorted-scale model requires that kinematic similarity and dynamic similarity also exist. Kinematic similarity exists when the ratios of all homologous velocities and accelerations are equal in the model and prototype. Dynamic similarity requires that the ratios of all homologous forces be the same in the model and prototype. Since force is related to the product of mass and acceleration, dynamic similarity implies the existence of kinematic similarity which, in turn, implies the existence of geometric similarity.

c. For dynamic similarity, the ratio of the inertial force between model and prototype must be the same as the ratio of the individual force components between the model and prototype. The ratios of the inertial force to the other component forces must also be the same between model and prototype. These ratios have developed a reference to specific names, such as the ratio of the inertial force for the pressure force as:

$$E_n = \frac{F_i}{F_{pr}} = \frac{p}{\rho V^2} \text{ (Euler No.)} \tag{B-1}$$

$$F_n = \frac{F_i}{F_g} = \frac{V}{(gL)^{1/2}} \text{ (Froude No.)} \tag{B-2}$$

$$R_n = \frac{F_i}{F_\mu} = \frac{VL\rho}{\mu} \text{ (Reynolds No.)} \tag{B-3}$$

$$W_n = \frac{F_i}{F_{st}} = \frac{\sigma}{\rho V^2 L} \text{ (Weber No.)} \tag{B-4}$$

Since only three of these equations are independent, the Euler number will automatically be equal. in the model and prototype if the other numbers are equal. For the remaining three equations,

$$\left[\frac{V}{(gL)^{1/2}}\right]_r = \left(\frac{VL\rho}{\mu}\right)_r = \left(\frac{\sigma}{\rho V^2 L}\right)_r = 1 \tag{B-5}$$

It can be demonstrated that no single model fluid will permit all of these equations to be satisfied at once. Therefore, absolutely true dynamic and kinematic similarity apparently cannot be achieved between a model and the prototype. However, one or more of the specific forces are often found to be negligible, and the number of equations to be satisfied can be reduced accordingly. In fact, the phenomena in a particular instance often involve the effect of only one force ratio, and the others are negligible.

d. The use of water as a model fluid is usually necessary in physical coastal models. Surface tension, the least important term if the depths of the fluid are not excessively small, will have a negligible effect on the flow of water more than 0.25 foot deep, or on waves with lengths exceeding about 1 foot in the same water depth. By ensuring that the flow and waves exceed these limiting values, the effect of surface tension can be neglected.

e. When both viscous and gravity forces are important, the Froude and Reynolds numbers should both be satisfied simultaneously. This requirement can only be met by choosing a special model fluid. Since water is the only practical model fluid, an approximate similarity requirement may be used, based on empirical relationships which include the major effects of frictional forces (such as Manning's equation). Since fairly high Reynolds numbers are usually associated with tidal flows through coastal models, the shear stresses are primarily determined by form drag. The use of Manning's formula as a similarity criterion requires that the flow be fully rough turbulent in both the model and prototype. When a bulk Reynolds number, defined as $Vd/<$, is greater than about 1,400 (where d is the depth of flow and $<$ is the kinematic viscosity), fully rough turbulence will normally exist. A surface gravity wave is essentially a gravitational phenomenon; therefore, the controlling criterion of similitude is the Froude number, and waves may be represented correctly in undistorted-scale coastal models.

f. There are several physical interpretations that may be given the Froude number, but fundamentally it is the ratio of inertial to gravitational forces acting on a particle of fluid. It can be shown that this ratio reduces to $V/(gL)^{1/2}$, where V is a characteristic velocity, and L is a representative length. Here the velocity is taken to be a horizontal length divided by the time parameter. However, any representative velocity and any representative length can be used in the Froude number as long as dynamic similarity is maintained and corresponding regions are considered in the model and prototype. The Froude number, defined as $V/(gd)^{1/2}$, is related to the vertical scale (depth), so that the velocity ratios are equal to the square root of the depth ratios. The pertinent ratios required for geometric, kinematic, and dynamic similarity, based on the Froudian similarity criterion, are developed in Table B-1.

B-11. Physical Coastal Model Design.

a. After the purpose of the coastal model study has been defined, the actual design of the model can proceed. The significant steps are acquisition of prototype data to assure model accuracy, establishment of model limits, and definition and acquisition of model appurtenances.

TABLE. B-1

Froude Criteria Scaling Relationships for Physical Coastal Models

	Undistorted-scale model	Distorted-scale model
	Geometric similarity	
Length	L_r	
(horizontal)		$(Lh)_r$
(vertical		$(Lv)_r$
Area	L_r^2	
(horizontal)		$(Lh)_r^2$
(vertical)		$(Lh)_r(Lv)_r$
Volume	L_r^3	$(Lh)_r^2(Lv)_r$
	Kinematic similarity	
Time	$L_r^{1/2}$	$(Lh)_r/(Lv)_r^{1/2}$
Velocity	$L_r^{1/2}$	$(Lv)_r^{1/2}$
Acceleration	1	1
Discharge	$L_r^{5/2}$	$(Lh)_r(Lv)_r^{3/2}$
Kinematic viscosity	$L_r^{3/2}$	$(Lv)_r^{3/2}$

(Continued)

TABLE B-1 (Continued)

	Undistorted-scale model	Distorted-scale model
	Dynamic similarity	
Mass	L_r^3	$(Lh)_r^2(Lv)_r$
Force	L_r^3	
(horizontal)		$(Lh)_r^3$
(vertical)		$(Lh)_r^2(Lv)_r$
Dynamic viscosity	$L_r^{3/2}$	$(Lv)_r^{3/2}$
Surface tension	L_r^2	$(Lh)_r^2$
Pressure intensity	L_r	$(Lv)_r$
Impulse and momentum	$L_r^{7/2}$	$(Lh)_r^2(Lv)_r^{3/2}$
Energy and work	L_r^4	$(Lh)_r^2(Lv)_r^2$
Power	$L_r^{7/2}$	$(Lh)_r(Lv)_r^{5/2}$

b. The importance of accurate prototype data cannot be overemphasized in model operation. The accuracy of the model is dependent on the use of proper field data. Although the similitude of fixed-bed, undistorted-scale models indicated that good approximation of bed-form losses can be derived in the model, assurance of accurate model results can only be achieved through a comparison of model and prototype results. To assure that the model is a geometric reproduction of the prototype, hydrographic and bathymetric surveys must include the pertinent bay and ocean approaches that influence the study region.

c. The final proof of model effectiveness is a comparison of current velocities and water surface elevations in both the model and the prototype. The requirements for a particular coastal model can vary extensively; however, a limited number of critically placed tide gages and wave gages, along with carefully located velocity stations, can provide enough information for confidence in the model operation.

d. The appurtenances required for an effective model study include:

(1) A tidal reproducing system for the ocean.

(2) A tide reproducing system for the bay if the bay is not completely modeled.

(3) Wave generator or generators.

(4) Tidal height measuring and recording system.

(5) Velocity measuring and recording system.

(6) Wave measuring and recording system.

(7) Photographic capabilities.

(8) Specialized equipment appropriate to the specific study under evaluation.

Each of these systems requires proper planning in designing the model as construction of the model depends on advanced knowledge of the specific requirements of each system.

B-12. Physical Coastal Model Construction.

a. Among the details that must be planned in model construction are the various modifications (plans) which will be evaluated during the model study. If, for example, the effects of dredging a feature (navigation channel, harbor, turning basin, etc.) are evaluated, the construction of the model should be based on this information. The templates prepared from detailed hydrographic and bathymetric maps to assure that the model is a true representation of the prototype should be modified to include the deepest possible navigation channel, deposition basin, turning basin, etc. This modification would allow the study of these features in later stages of the model testing program. A second set of templates can then be installed in the molded model to allow features of lesser depth to be incorporated into the model. Tests can then be conducted with the conditions of lesser depth in the model; when tests are completed, conversion of the model to evaluate a proposed change can be easily accomplished.

b. The construction of the coastal model requires the proper planning and sequencing of:

(1) Basic site preparation.

(2) Installation of buried features (i.e., pipelines, required bases for instrumentation support systems, etc.).

(3) Installation of control templates.

(4) Installation of base material.

(5) Placement of material (concrete, sand, etc.,) forming the model.

(6) Finishing the model for the desired surface texture.

(7) Fabrication and installation of tide-generating capabilities.

(8) Installation of wave generators, velocity recording systems, tide recording systems, wave recording systems, and photographic capabilities.

(9) Installation of other specialized monitoring equipment necessary to evaluate effects of proposed coastal projects on specific environmental or ecological parameters.

B-13. Fixed-Bed, Undistorted-Scale Coastal Models.

a. For coastal studies not concerned with the movement of sediments, fixed-bed models can often be easily developed to provide kinematic and dynamic responses indicative of the prototype conditions. Specifically, fixed-bed models reveal information regarding velocities, discharges, flow patterns, water surface elevations, and energy losses between points in the prototype. In the superposition of surface gravity waves on the fixed-bed flow conditions, an undistorted-scale model ideally provides greater insight at less effort into the refraction and diffraction phenomena associated with the wave passing the underwater topography and around coastal features. Accordingly, the fixed-bed, undistorted-scale model can be effectively used for the analysis of kinematic and dynamic conditions associated with waves, current intensities and patterns, discharges, and forces existing along coasts and in bays or estuaries.

b. A fixed-bed model (although not is primary purpose) may also be useful in studying shoaling of entrance and interior inlet channels. Saltwater intrusion and the effects thereon of proposed changes in the physical or hydraulic regimes of the system can be effectively studied by fixed-bed models. The diffusion, dispersion, and flushing of wastes discharged into coastal regions, as well as the hydraulics as related to location and design of channels suitable for navigation, can be expediently studied. Tidal flooding by hurricane surges or other tidal phenomena can also be readily analyzed.

(1) Model verification.

(a) The verification of a fixed-bed, undistorted-scale coastal model consists basically of conducting sufficient tests in the model to reproduce model boundary conditions (i.e., ocean tides, ocean waves, bay tides, and current velocities). The model data are then compared with prototype data for duplicate locations in the model and prototype to define the accuracy with which the model reproduces the prototype. If reproduction of the prototype is not achieved, the differences are evaluated for possible sources of error. Frequently, the differences are a result of either incorrect location of roughness in the model or improper magnitude of model roughness. If the comparison shows isolated stations to differ, the differences are usually caused by incorrect model results or erroneous prototype data collection. Repeating the model test will clearly indicate which of these causes produced the difference between the model and prototype information. If it is concluded that the model data were in error, then new model data can be quickly obtained.

(b) Model verification can also include definition of the model operating characteristics required to achieve reproduction of fixed-bed shoaling patterns throughout the coastal model. This procedure consists of a trial-and-error operation until the model operating conditions required to reproduce known changes in prototype shoaling are developed.

(2) Model tests.

(a) Tests in undistorted-scale, fixed-bed models can provide useful information on not only the hydrodynamics of a coastal region but also the expected changes to the hydrodynamics due to changes in the region. An effective model test program should include initially a complete set of tests to define the conditions that exist in the model for hydrographic, bathymetric, topographic, and hydraulic conditions for which the model was verified. These data then form the base conditions to which all future tests can be compared to evaluate the effects of changes to the coastal area under consideration.

(b) The data obtained from the model for the base conditions should include: detailed current velocities at critical locations throughout the model for a complete tidal cycle, detailed surface current patterns of the entire area of interest at incremental times throughout the tidal cycle, detailed wave characteristics throughout the inlet for an array of expected prototype conditions, and a complete documentation of tidal elevations throughout the area of interest. The evaluation of a particular proposed change in the model duplicates the procedure followed in obtaining a base set of data and compares the results of each set of data.

B-14. Fixed-Bed Distorted-Scale Coastal Models.

a. Physical coastal models are frequently distorted for various reasons. Many regions of interest are large and flood and ebb tidal deltas may be quite shallow, leading to large model energy attenuation and viscous friction scale effects on waves. These effects can be minimized through distortion and at the same time decrease model costs. Reproduction of the entire tidal estuary in the model is often desirable, since inclusion of the tidal estuary results in the flexibility to study the effects of proposed improvements on the tidal prism, tidal circulation, tidal flushing, and salinity of the estuary. Inclusion also results in the correct nonlinear energy transfer from various tidal constituents to higher order harmonics. Deletion of a major part of the estuary leaves reproduction of this phenomenon more uncertain.

b. Distorted-scale models for use in the study of coastal harbors, inlets, etc., have generally been universally accepted. The horizontal scale ratio is often dictated by the size of the facility in which the model is placed or the construction cost. The vertical scale ratio needs not be larger than the ratio of model measurement accuracy to prototype measurement accuracy. The accuracy of laboratory measurements of water surface is generally on the order of 0.001 foot; the accuracy of prototype measurements varies with equipment and field conditions but is generally within 0.1 foot. Thus, a vertical scale ratio, model-to-prototype, of 1:100 will fully utilize the capabilities of the model in simulating the prototype. Models of larger vertical scale are often used to simplify operational techniques and to assure model depths larger enough that surface tension does not affect flow.

c. A second factor to be considered in the selection of scales is the "distortion." Distortion is the ratio of the horizontal scale to the vertical scale, and its value relates the order that all slopes of the prototype are steepened in the mode. In the study of coastal regions, particularly with movable-bed models, efforts are made to design models with distortion values of five or less. Otherwise, the slopes required in the movable-bed model for accurate reproduction of the prototype may be steeper than the angle of repose of the model material, thus creating a difficult scale effect to overcome. This point is emphasized because coastal models are often constructed with both a fixed bed and a movable bed, and with a distorted scale. Vertical scale ratios, model-to-prototype, are generally in the order of 1:40 to 1:100; horizontal scale ratios are generally in the order of 1:100 to 1:500.

d. Distorted-scale coastal models are frequently constructed for multiple purposes, e.g., an investigation of an inlet may be necessary where a jetty is to be installed. A prediction will be required of the effects of the jetty on tidal currents and water levels near the inlet and also the degree to which the jetty interrupts the littoral drift and affects deposition patterns near the inlet. Other water quality and biological questions may also be addressed in such a coastal model study at the same time. In this case, a multipurpose model is needed. This model would first be built with a distorted-scale, fixed-bed design and then adjusted and tested to determine the effects of the jetty on tidal heights and currents. A segment of the fixed part of the model surface would then be carefully removed and replaced with a movable material to evaluate the effects of the jetty on the littoral drift or other phenomena of interest.

e. Model verification and testing in a distorted-scale, fixed-bed model follow essentially the same procedures as for an undistorted-scale, fixed-bed model. However, because of distortion effects, the transference equations from the model to a prototype situation are, in general, completely different.

B-15. Movable-Bed Coastal Models.

a. Theoretical Aspects of Movable-Bed Modeling.

(1) The movement of loose bed material is governed by the inertial forces of the particles and of the water against them, by the weight of the particles, and by the viscous forces acting between the water and the particles. Three physical laws have evolved from an analysis of these forces: Newton's law of inertia, the law of gravitation, and the viscous friction law of Newtonian fluids. These laws have provided two well-known dimensionless terms which must be equated between the model and the prototype for kinematic and dynamic similarity to prevail; i.e., the Reynolds Number, R_n, and the Froude Number, F_n, expressed as

$$R_n = \frac{Vd}{\nu} \qquad \text{(B-6)}$$

and

$$F_n = \frac{V}{(gd)^{1/2}} \qquad \text{(B-7)}$$

where V is the fluid velocity, d is the depth of flow, < is the fluid kinematic viscosity, and g is the acceleration of gravity.

(2) The simultaneous conformation of the model and prototype to both the Reynolds number and Froude number yields the familiar problem that the length-scale factor becomes a function of the scale factor of the kinematic viscosity. This function determines that no readily available fluid possesses the kinematic viscosity to make a useful model fluid. Schuring (1977) reasons that since the same fluid for model and prototype provides less than perfect similarity but probably must be used, design requirements can be relaxed if the inertial forces of the sediment are much smaller than the rest of the forces and, therefore, can be neglected. Then Newton's law of inertia must only be applied to the fluid. A further simplification, without loss of

generality, is achieved by restricting the law of gravitation to the weight difference of water and sediment. With these two modifications, a qualified Froude number evolves, often referred to as a densimetric Froude number, and the length-scale factor is freed from its dependence on kinematic viscosity:

$$F_* = \frac{V}{\left[\left(\frac{\rho_s}{\rho_w} - 1\right) gd\right]^{1/2}} \tag{B-8}$$

The penalty for this simplification is a restriction of the particles to a state of rolling or sliding with small or no inertial forces acting upon them. The model becomes invalid when the particles begin to leave the bed and are carried upward, such as in the surf zone or in relatively shallow water affected by surface gravity waves. Very good correlation between variables was achieved in flume experiments with unidirectional flow (Schuring 1977).

(3) A different approach, advanced by Gessler (1971), assumes that both the prototype sediment and the material used as model sediment are given, and the model geometric scales are determined to fit the requirements of these materials. In this approach, supplemental information should be used in the form of the Shields parameter regarding the critical tractive force necessary to produce incipient motion. However, model scales based on the principles of unidirectional motion may not be strictly applicable to the case of oscillatory wave motion, but a first approximation is probably permissible. By setting a lower limit to the model Reynolds number and computing the prototype Reynolds number, the ratio of the prototype-to-model Reynolds number will determine the scale of the characteristics length used in the vertical direction of the model. In this procedure, it is assumed that the ratio of model-to-prototype velocity is a function only of the depth ratio, as determined by the Froude law.

(4) If the model sediment material has not been selected beforehand, a revised approach can be developed (Gessler 1971). To have similarity in incipient motion and bedload transport, the bed mobility in the model and prototype should be the same at homologous points. This mobility is determined by the ratio of the actual Shields parameter to the critical Shields parameter. The reason for this modification in approach is that the critical Shields parameter depends somewhat on the grain Reynolds number for values below about 150. For ordinary model materials (fine-grained sands), the grain Reynolds number is on the order of 5 to 10. The Shields diagram is poorly verified in this range, so the grain Reynolds number should not be smaller than about 15. This grain Reynolds number can be achieved by using a coarser bed material in the model than in the prototype, but one that is less dense. The Shields parameter is

$$\tau_* = \frac{\gamma_w dS}{(\gamma_s - \gamma_w)D_s} \tag{B-9}$$

where S is the bed slope and d is the particle size. By using this definition and evaluating the ratio of the prototype-to-model Shields parameter, a generalized criterion will evolve which can be solved for the specific weight (submerged) of the bed material to be used in the model. The reason for using a lightweight material refers to the idea that the grain size is relatively too large in the model. The final selection of the model material will depend on the materials available; however, a slight adjustment in the desired grain size may be necessary.

(5) The analyses of Gessler (1971) are applicable only to unidirectional flow at one specific discharge; thus highly unsteady flow processes like surface gravity waves cannot adequately be modeled by this process. Changes in discharge require that the time scale of the discharges be modeled according to the time scale associated with the sedimentation process to obtain similarity in bed-forming processes. The considerable discrepancy between the hydrodynamic and sedimentological time scales means that the sedimentation processes are advancing too rapidly in the model. Gessler (1971) concludes that no matter how carefully the design is done, it remains absolutely essential for distorted-scale as well as undistorted-models to be verified against field data.

(6) When studying problems of scour and deposition, it becomes necessary to add the critical shear stress and sublayer criteria to the gravity and frictional criteria, as developed by Graf (1971). Introducing the empirical relationship between the bed particle diameter and Manning's n value produces

$$(d_r)^{1/6} = n_r = (R)_r^{2/3} \left(\frac{1}{L_{h_r}}\right)^{1/2} \tag{B-10}$$

where d is the bed particle diameter and R is the hydraulic radius. When model and prototype fluids are identical, four independent variables are found, and three equations provide a solution. The problem is determined if one of the four parameters is chosen, and the remaining three variables are found from the equation solutions. A distorted-scale model was assumed in this analysis. Various researchers have stated that some model laws can be relaxed with little harm to the overall investigation. Einstein and Chien (1954) suggested that the friction criterion, the Froude criterion, or the sublayer criterion might absorb further distortions. Under certain circumstances, small deviations from the exact similarity may be allowed, making it possible to arbitrarily select more than one single variable.

(7) For the application of strictly coastal sediment modeling problems, Migniot et al. (1975) have stated that since all of the similitude conditions involved cannot be satisfied, the model scales, the material size and density, and the current exaggeration cannot be determined by straightforward computations but must be chosen to obtain the most favorable balance between all relevant phenomena. In many respects, movable-bed physical modeling is more an art than a science. A feeling of the problem, previous experience, and a perspective of the relative importance of each factor are of paramount value in applying the method. The sedimentological time scale can be derived from general transport formulas. When sand is simulated with a lightweight material such as plastic with a density of 1.4, the sedimentological time scale will be in the range of 1:1,000 which means that a year will correspond to some 8 hours of model time. Although it is disquieting to note that so much empiricism prevails in the design of coastal movable-bed models, the model is only fit for predictive use when it has successfully reproduced past evolution. While the various similitude conditions may not all be satisfied, the conditions do not differ too much from each other, so fairly satisfactory compromises can usually be found. For instance, model material density required to satisfy these various prototype conditions may typically vary from 1.3 to 1.6, while size exaggeration may vary from 1.0 to 1.7.

(8) The movable-bed coastal model by Kamphuis (1975) is a wave model incorporating coupled wave motion and sediment motion relationships which have been determined experimentally. The unidirectional flow phase is then added to the basic wave model and adjusted to yield correct results for different situations. This philosophy is basically different from Le Méhaute (1970) who assumed that a coastal movable-bed model is a unidirectional flow model modified by waves. The difference in scale laws is quite evident when the results of their models are compared.

(9) According to Kamphuis (1975), the movable-bed phase of the model study is subjected to four relaxed basic scaling criteria: the particle Reynolds number, the densimetric Froude number, the relative density, and the relative length-scale relating water motion to sediment size. Ideally, all of these basic scaling criteria must be satisfied simultaneously but cannot be satisfied in practice. As more of these criteria are ignored, the model will perform successively less like the prototype, and scale effects (nonsimilarity between model and prototype) increase. Only a lightweight material can be used to keep the model and prototype particle Reynolds number identical. Any deviation from unity is rather small (in all cases) and is not considered to limit the model seriously. Similarity of the densimetric Froude number is considered to be the most important of the four modeling criteria. If the model densimetric Froude number is less than some critical value and the prototype number is greater than this critical value, the model is useless. The model and prototype densimetric Froude numbers should be equal, or incorrect scaling will result in considerable distortion of the sediment motion parameters with exaggerated time scales for sediment motion, and the model will take longer to move the material than it theoretically should. Thus, the sediment motion will start later in the model (in shallow water), but in the area where material moves freely, the nonsimilarity of the densimetric Froude

numbers will manifest itself in adjustment of the time scale for sediment motion. The time scale also varies with depth, and moreover, if initial motion and depositional patterns are important, it is necessary to model the densimetric Froude number correctly.

(10) The nonsimilarity of the model and prototype ratios of sediment particle density to water density affects the process in two distinct ways. The acceleration of the particle is changed, and the particle becomes relatively too heavy when no longer submerged. For a lightweight material, the individual particles are relatively heavier in the surf zone than if sand were used. Therefore, the beach material has a tendency to pile up immediately past the surf zone, and the particles will remain in this location because they become relatively heavier when not submerged. As a result, there is a highly distorted version of sediment transport in the surf zone. It is very difficult to duplicate prototype conditions in the littoral zone using lightweight materials.

(11) Coastal movable-bed models suffer from various scale effects when the particle sizes are not scaled down geometrically. Since this fact is true for most coastal movable-bed models, the prediction of bed morphology time scales is virtually impossible. Thus, verification using historical survey data remains a necessary step. Because of the variety of scale effects, coastal movable-bed modeling continues to be as much an art as an exact science.

b. Prototype Data Requirements.

(1) Perhaps the most important aspect of the design phase of a movable-bed coastal model study is to assure the adequacy of the prototype data. The model is constructed to conform to prototype surveys; adjustment of the model to accurately reproduce prototype hydraulics or sedimentation patterns is based on prototype measurements. Any errors or insufficiencies in prototype information will result in inadequate and incorrect performance of the model.

(2) Prototype information required for a movable-bed coastal model study includes geometry and sediment properties, adjacent beach configuration, wave measurements, littoral drift estimates, water surface time histories, and synoptic tidal currents in the ocean, bay, inlets, and harbors. The occurrence of storms of low-return frequency should be noted, since large volumes of sand can be displaced during these activities. Hydrographic and wave observations should also be made frequently enough to detect seasonal and yearly fluctuations.

(3) A longer data collection period is needed for a movable-bed study than for a fixed-bed model. The period length also varies with the data type; e.g., longer term wave data are needed than tide level and current data to calibrate a movable-bed model. Prototype observations for several consecutive years before the model study will allow an evaluation of both short- and long-term tendencies of the coastal region -and the selection of a typical period on which to base the model verification. A three-year documentation period is

probably the minimum length, since major trends cannot usually be detected in shorter time periods.

c. Model Verification.

(1) The verification phase of a coastal movable-bed model study is perhaps the most important. A well-accomplished verification will minimize or eliminate the effects of small errors in construction and will allow the evaluation of the effects of poorly understood variables on the coastal region during the testing phase. Verification requires the adjustment of model boundary conditions to recreate or correct conditions that were altered in the scaling process. Sedimentation verification is based on prototype observations and is accomplished by selecting an appropriate model sediment and developing the necessary model operating technique to reproduce the observed scour and fill patterns. Verification of a coastal movable-bed model is, theoretically, more difficult than for a fixed-bed model. The purpose of a movable-bed model is to simulate the evolution of the coastal bathymetry. This evolution takes place in response to many factors, but primarily to the sediment washed from adjacent beaches by wave action, to erosion of the inlet channels by tidal currents, and to entrapment of material at the bars on the ocean and bay sides of the tidal inlets. Coastal harbors also accumulate littoral drift and shoal material. These same factors must be included in the model to simulate degree as well as type of bathymetry evolution.

(2) Since a movable-bed coastal model simulates shoaling and scouring patterns, the requirement that the model also simulate the basic hydraulic quantities (tidal heights, tidal phases, velocities, etc.,) is somewhat relaxed. In practice, the verification of a movable-bed coastal model is a little easier than for a fixed-bed model, since the experimenter has more variables available with which to work to achieve the desired verification. The validity of tests of proposed improvement plans in movable-bed model is based on the following premise: if model reproduction of the prototype forces known to affect movement and deposition of sediments (tides, tidal currents, waves, etc.) produces changes to model bed configuration similar to those observed in the prototype under similar conditions, then the effects of a proposed improvement plan on the movement and deposition of sediments will be substantially the same in both model and prototype.

(3) One of the most important reasons for the verification of a movable-bed coastal model is the establishment of the time scale with respect to bed movement. The model-to-prototype time scale for bed movement cannot be computed from the linear scale relations because the interrelation of the various prototype forces affecting movement and deposition of sediments is too complicated for accurate definition. Therefore, the time scale is determined empirically during the model verification; i.e., the actual time required for the model to reproduce certain changes that occurred in a given period of time in the prototype is used to determine the model time scale for bed movement.

d. Model Tests.

(1) The actual testing phase of a coastal movable-bed model is perhaps the easiest of all phases to accomplish. The model has been carefully designed and built based on measurements obtained from the prototype. The model has performed similarly to the prototype by responding to events to which it was subjected during verification in the same manner the prototype was observed to response when similar events occurred in its history. The model may now be justifiably expected to respond as the prototype would respond to an event or sequence of events, which has not yet occurred to the prototype at the particular point being investigated, for the same hydrography and operating conditions. This response of the model is termed the "predictive capability" of the model, since the behavior of the prototype under similar conditions can be inferred from that response.

(2) A model test series always involves at least two separate tests. The first test is a "base" test, which studies the existing coastal region and provides a basis for comparison with later tests that have alternative plans. The next test or tests in the series are the "plan" tests, so-called because the plan or plans for improving the coastal region are installed in the model and tested. The plan tests are always conducted with model conditions identical to those of the base test. This test procedure allows straightforward interpretation of the test results, as differences in results are attributable to the plan under investigation although some differences may occur because similitude criteria have not been completely satisfied.

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